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Carbon flow of urban system and its policy implications: The case of Nanjing

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ABSTRACT

China is now in the process of rapid urbanization. City's operating efficiency was directly determined by the scale and efficiency of energy consumption and flow. The pattern, scale and efficiency of urban carbon flow are not only important indicators that reflect urban efficiency and sustainable development, but also important references in the formulating low-carbon and sustainable energy polices for cities. Through establishing a theoretical framework and calculation method, this paper studied the carbon flows of Nanjing urban system in three different levels. It shows that urban production and transportation system, urban living system, rural production system and rural living systems are the major part of urban system in the carbon flow. The carbon flows between Nanjing and the external system, was much higher than the carbon flows among different internal subsystems. If the embodied carbon is taken into account, carbon flow from the urban to rural system of Nanjing was clearly greater than the flow in the opposite direction. With economic development and the implement of energy-saving and emission reduction policy, the carbon productivity and carbon flow efficiency in Nanjing has improved significantly since 2000. Fossil energy consumption, urbanization, agricultural activities, rural life demands and trade are key factors with major impact on urban carbon flows in Nanjing. Therefore, adjusting industrial structure, urban expansion control, and developing renewable energy are main measures to realize sustainable development of Najing city. Furthermore, the dual urban–rural structure in Nanjing brought large exchanges of products and embodied carbon between urban and rural areas, indicates that urban carbon flow and its efficiency was highly influenced by urban–rural structure, which will further aggravate carbon flow burden of urban systems.

Contents

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1. Introduction

Cities are the areas most profoundly influenced by human activity, for they are where human energy activity and carbon emissions concentrate. Arguably more than 80% of carbon emissions originate from urban areas [1], which occupy less than 2.4% of land mass globally [2]. As very open social-economic systems, there is huge carbon flows and exchange in urban systems as well as between those systems and the external system. Thus, the carbon cycle and circulation process of urban systems inevitably affect the regional and even global carbon cycle. Therefore, the study on urban carbon flow and its efficiency is very meaningful for comprehensively assessing the city's role in the regional carbon cycle, for establishing low-carbon urban energy and industrial strategies, and for raising energy efficiency of the urban system.

Urban carbon cycle simulation requires observations of both natural and anthropogenic carbon processes in urban system, as well as their interactions [1]. Since 2000, there appeared case studies on simulating carbon fluxes through the vegetation-soil component of an urban system [3–7]. In recent years, researchers have begun simulating social components of the carbon cycle in urban systems, such as studies on carbon effect of urbanization and land use [8–10], urban carbon budget [11,12], population, energy consumption and carbon emissions [13–16] and urban carbon flows [17,18]. Carbon cycle and carbon flows were simulated on different spatial scales: national [19], regional [20] or neighborhood level [21], which showed that the socio-ecological processes will highly impact the regional carbon budget [20]. The above studies greatly contribute to the modelling of carbon flow simulation in urban system. But the inner carbon flows among different urban sub-systems should be further studied, which is very important for the detailed designing of sustainable energy policies and city planning strategies.

Furthermore, there have been recent researches on urban metabolism simulation [17,22,23], which mainly focused on urban food carbon flow and metabolism [24,25], energy circulations [26] and carbon flux simulation [23,27]. Although metabolism method has been applied for metals, nutrients, and many other substances on various scales for decades, the systematic simulation of carbon flows by metabolism method on city or regional level just appeared in 2012 [20,23,27]. Generally, these studies of urban metabolism were mostly aimed at certain aspects of urban carbon processes. The direct and embodied carbon flows between urban and rural system and among different sub-systems were not fully discussed. It is quite different on individual carbon consuming habit, industrial and production structure and carbon flow characteristics between urban and rural systems. To explore effective strategies for urban energy and carbon management, systematic study of carbon flows in urban system should be strengthened. China is currently in a rapid urbanization process. The rapid economic growth led to more and more energy consumption [28]. China's urban areas contribute 75% of total primary energy demand, 85% of commercial primary energy demand, and 85% of the energy-related CO_2 emissions [29]. The intensity, scale and influences of urban carbon flows are increasing. But the systematic urban carbon flow study has not yet been appeared so far in China. Therefore, research on urban carbon flows and its efficiency not only helps to understand the mechanism of carbon processes, but also will be of great significance in the formulation of low-carbon energy policies for urban carbon management and carbon emission reduction in Chinese cities.

Nanjing, a rapidly developing city in eastern China, has a heavy chemical industry, so traditional energy consumption and the corresponding carbon emissions in Nanjing will increase rapidly. With rapid economic growth and urban expansion and high environmental pressure, Nanjing is representative of developing cities in China. Therefore, we selected Nanjing as a case study. Through carbon flow mechanism analysis and calculation method, we established a carbon flow map among different subsystems of Nanjing urban system, and evaluated carbon flow details and efficiency in Nanjing. This research can provide theoretical and practical guidance for urban energy management and low-carbon energy policies in different sectors of Nanjing city, and will helps to find a feasible way of sustainable development and emission reduction for Cities in China.

2. Carbon flow mechanism of the urban system

2.1. Definition of carbon flow in urban systems

The urban system is huge and complex, and includes natural, economic and social processes. Inside that system, and between the internal and external system, carbon in organic or inorganic form is continuously produced, decomposed, emitted, sequestered, transformed, circulated, input and output, which is called “urban carbon cycle”. The urban carbon cycle process is a “natural–social dualistic carbon cycle”, which includes carbon processes of natural ecosystems (such as carbon absorption by photosynthesis and carbon emission through respiration of vegetation or soils) and also carbon metabolism, input and output processes caused by human activities within urban social–economic systems (such as

carbon flows in the form of energy, foods, woods, books and building materials). Here, we call the natural carbon cycle the "biogeochemical cycle," and anthropogenic (or social–economic) carbon cycle "carbon flows." By their interaction, an entire urban carbon cycle system is formed, in which, human carbon flows are the key to understanding the mechanism of the urban carbon cycle.

Urban carbon flows include several different forms of anthropogenic carbon processes, as follows: (a) emission flow means the vertical form of carbon flows (in the form of carbon dioxide); (b) trade flow means all the horizontal form of carbon flows (in the form of carbohydrate) [1]; (c) carbon metabolism is the processes of processing, consuming and transformation of carbonic materials in urban systems, such as food consuming and industrial processing; (d) carbon input and output means the carbon importing in and exporting out of urban system respectively. Actually, carbon input and output are also forms of urban trade carbon flows.

2.2. Carbon flow mechanism and division of the urban system

From the above analysis, we see that urban carbon flows include all types of direct and indirect (embodied) carbon cycle processes in the urban system, and between the urban and external system. Generally, according to various circulation paths and scope, carbon flows of the urban system can be divided into the following three levels:

(1). Carbon flows between urban and external system. This includes carbonic material input and output from the urban system. The former includes fossil fuels, timbers, foods, furniture, books and building materials that are input to the urban system. The latter includes energy products, goods and wastes containing carbon that are output from the urban system.

(2). Carbon flows among different inner sub-systems of the urban system. This includes all goods and materials that contain carbon, transforming and circulating among the urban production, urban living, rural production and rural living systems. This includes energy supply, food transportation and consumption, raw material supply, goods production and transport.

(3). Embodied carbon flows between the urban and rural system. Here, embodied carbon means carbon emission from energy consumption in the production processes of all industrial products used for trade, which is generated by urban or rural demands. This includes indirect carbon embodied in products and electricity, from the urban production system to the urban and rural living system or external system.

To further understand the carbon flow processes, the urban system was divided into four sub-systems: urban production and transportation system, urban living system, rural production system and rural living systems. The main carbon flows among them are shown in Fig. 1.

3. Calculation method for carbon flows in urban system

According to the theoretical framework (Fig. 1), the carbon flows of the urban system was estimated and analysed through the following calculation methods, and the carbon flows of three carbon-related products (energy, foods and woods) were analysed.

3.1. Carbon emissions from urban energy consumption

Based on common research methods and the calculation method of the International Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (2006), carbon emission from urban energy consumption was estimated with the following:

$$CE_{energy-i} = Q_{energy-i} \times H_{energy-i} \times (C_{energy-i} + M_{energy-i}), \quad (1)$$

where $CE_{energy\text{-}i}$ is carbon emission from energy consumption type i, $Q_{energy\text{-}i}$ is energy consumption type i, $H_{energy\text{-}i}$ is net calorific value of energy type i, $C_{energy\text{-}i}$ is CO_2 emission factor of energy type i, and $M_{energy\text{-}i}$ is CH_4 emission factor of energy type i. $H_{energy\text{-}i}$ was derived from the *China Energy Statistical Yearbook* [30], and carbon emission factors of each energy type were from IPCC [31] (Table A1).

3.2. Carbon flows of urban food consumption

3.2.1. Carbon content of foods

Carbon content of food is really carbon absorption during the growth of crops by photosynthesis. Therefore, it can be estimated by the following method:

$$CI_{crop} = \sum_i CI_{crop-i} = \sum_i C_{crop-i} \times Y_{bio-i} \times (1 - P_{water-i})$$
$$= \sum_i C_{crop-i} \times (1 - P_{water-i}) \times \frac{Y_{eco-i}}{H_{crop-i}}, \quad (2)$$

where CI_{crop} is total carbon content of crops, $CI_{crop\text{-}i}$ is carbon content of crop type i, $C_{crop\text{-}i}$ is carbon absorption rate of crop type i, $Y_{bio\text{-}i}$ is biological yield of crop type i, $Y_{eco\text{-}i}$ is economic output of crop type i, $H_{crop\text{-}i}$ is economic coefficient of crop type i, and $P_{water\text{-}i}$ is moisture content of crop type i. $H_{crop\text{-}i}$, $C_{crop\text{-}i}$ and $P_{water\text{-}i}$ of principal crops (Table A2) were derived from several references [32,33].

3.2.2. Carbon flows by urban food consumption

Carbon input to an urban system can be estimated by per capita food consumption and the city population. The method is as follows:

$$CI_{food} = \sum_i Q_{food-i} \times C_{food-i} \times (1 + 30\%), \quad (3)$$

where CI_{food} is carbon content of food input to the urban system, $Q_{food\text{-}i}$ is carbon consumption of food type i, and $C_{food\text{-}i}$ is carbon content reference of food type i (Table A3). Considering that there may be some food consumption not included in the statistical data, such as restaurant consumption, travel food consumption and other snacks. Here, the proportion of 30% was used in estimating this section of food consumption according to the average statistical proportion from the questionnaire survey in several residential communities of Nanjing. Further, carbon of food consumption will be emitted through food waste, respiration and excretion, in which food consumed and wasted accounts for 70.1% and 29.9% [17], respectively. For carbon emitted from food consumed, the proportions of respiration and excretion are about 50.3% and 19.7%, respectively [17].

3.3. Carbon flows of urban timber production and use

Local carbon flows of timber were estimated by local felling of trees, and consumption of timber in the city was calculated by its demand for products such as construction wood, books, and furniture. Carbon input to the city in the form of construction wood was estimated by annual floor area increase. The method is as follows:

$$CI_{build} = Area_{new-build} \times Wood_{unitarea} \times wood_{dens} \times C_{wood} \quad (4)$$

$$CI_{fit} = Area_{new-build} \times Wood_{unit-fit} \times wood_{dens} \times C_{wood}, \quad (5)$$

where CI_{build} is carbon content of annual construction wood increase, CI_{fit} is carbon content of annual decorating wood increase, $Area_{new\text{-}build}$ is annual floor area increase, and $Wood_{unitarea}$ is wood consumed in the construction process of unit floor area.

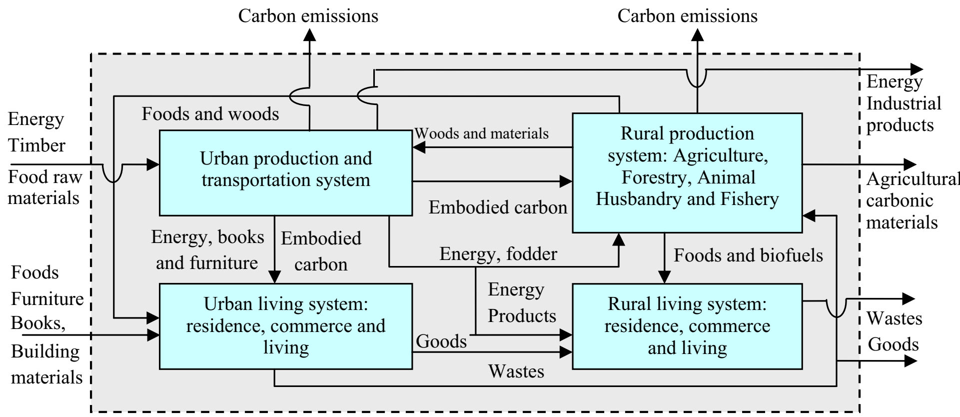


Fig. 1. Carbon flow framework of urban system.

The latter includes three building types: urban residential, urban public and rural residential. $Wood_{unitarea}$ for these three building types is 0.045, 0.055 and 0.06 m^3/m^2, respectively [34]. $Wood_{unit\text{-}fit}$ is wood used for decoration of unit floor area (0.014 m^3/m^2) [35]. $Wood_{dens}$ is the average density of wood products (0.485 t/m^3)[36], and C_{wood} is carbon content of timber (0.5 t/t) [36]. Wood used annually in projects under construction (such as buildings, bridges and water conservancy facilities) was estimated at 2% [35] of total wood consumed in buildings.

Carbon in furniture and books was estimated by wood used in the production process. Carbon of books was estimated at 50% (carbon content rate) [35] of book output. Carbon of furniture was calculated by the following method:

$$C_{furn} = Q_{furn} \times 49.67\% \times 0.0478 \times 0.485 \times 0.5 \quad (6)$$

where C_{furn} is carbon content of furniture and Q_{furn} is the output of furniture. According to Ref. [34], wood furniture accounts for 49.67% of all furniture, the average wood content of wooden furniture is 0.0478 m^3, the average density of timber is 0.485 t/m^3, and the carbon content of timber and paperboard is 50%.

3.4. Embodied carbon flows between urban and rural systems

According to product yield and carbon emission amount of each industry, the carbon embodied in a unit product of each industry can be calculated. Then, embodied carbon flows and proportions between urban and rural systems can be calculated, according to the amount of products from each industry consumed in urban and rural systems. The method is as follows:

$$C_{em-rural} = \sum \frac{CE_{ind-i}}{P_{ind-i}} \times Q_{rural-i}, \quad (7)$$

where $C_{em\text{-}rural}$ is carbon embodied in products consumed by the rural system, $CE_{ind\text{-}i}$ is carbon emission from energy consumption of industry type i, $P_{ind\text{-}i}$ is the product yield of industry type i, and $Q_{rural\text{-}i}$ is rural product consumption of industry type i.

$$C_{em-city} = C_{em-total} \times (1 - P_{out}) - C_{em-rural}, \quad (8)$$

where $C_{em\text{-}city}$ is carbon embodied in products consumed by the urban system, $C_{em\text{-}total}$ is total carbon embodied in urban industrial products, and P_{out} is the output proportion of industrial products. Because consumption proportion data of each industry cannot be easily collected, products consumed in urban and rural systems were determined by the proportion of consumption expenditure in those systems annually.

3.5. Estimation of other carbon flows of urban system

(1). Carbon emission from straw combustion was estimated by the combustion proportion[1] of the straw of principal crops.
(2). Carbon emission from bio-energy such as methane and firewood was also calculated by formula (1), with the parameter from Table A1.

3.6. Uncertainty analysis of urban carbon flows through Monte Carlo simulation

Some parameters used in the above calculations were derived from the literature, such as the proportions of wood furniture and human food waste, additional food consumption, and others. Some carbon flows are ignored in the calculations, such as import or export trade flows, living bio-mass flows, production waste and loss, petrochemical products. Therefore, there is uncertainty in the carbon flow estimation.

Monte Carlo simulation has been widely used in the prediction of stochastic processes. In recent years, it has been used in uncertainty analysis of carbon emissions [37,38]. The method was adopted here to analyse uncertainty of carbon flows. First, the distributions of several assumption and uncertainty items were defined, which include normal and triangular distributions (Table 1). Then, through 50 thousand trials with confidence level 95% and using the software Crystal Ball, the distribution of uncertain carbon flows was obtained.

3.7. Sources of data

Most of our data comes from yearbooks and government reports, as shown in Table A4.

4. Results

To understand the direction and scale of inner carbon flows, through detailing the inner carbon consumption path of the urban system, a carbon flow map of the Nanjing urban system in 2009 was drawn by determination of several sub-systems and their carbon relationships according to Fig. 1. We see that the “rural production system” in Fig. 1 was divided into four sub-systems: agriculture, forestry, animal husbandry, and fishery (Fig. 2). These four sub-systems, together with rural residential, commercial and

[1] Municipal Development & Reform Commission of Nanjing. The “twelve-fifth” Straw Utilization Plan of Nanjing; 2010.

Table 1
Assumptions definition of several uncertain carbon flows in Nanjing.

Assumption items	Distribution	Parameters
Proportion of imported flows	Triangular	Minimum: 24.4% Likeliest: 32.8 Maximum:42.9
Proportion of exported flows	Triangular	Minimum: 29.8% Likeliest:41.2% Maximum:49.04%
Living bio-mass per unit area(t/h m^2)	Triangular	Minimum: 31.11 Likeliest:32.1 Maximum:41.32
Other petrochemical products	Normal	Mean:3.5% Std. Dev.: 0.35%
Additional food consumption	Normal	Mean: 30% Std. Dev.:10%
Proportion of wood furniture	Normal	Mean: 49.67% Std. Dev.:10%
Proportion of food waste	Normal	Mean: 29.90% Std. Dev.:2.99%
Production waste and loss	Normal	Mean:5% Std. Dev.:1%

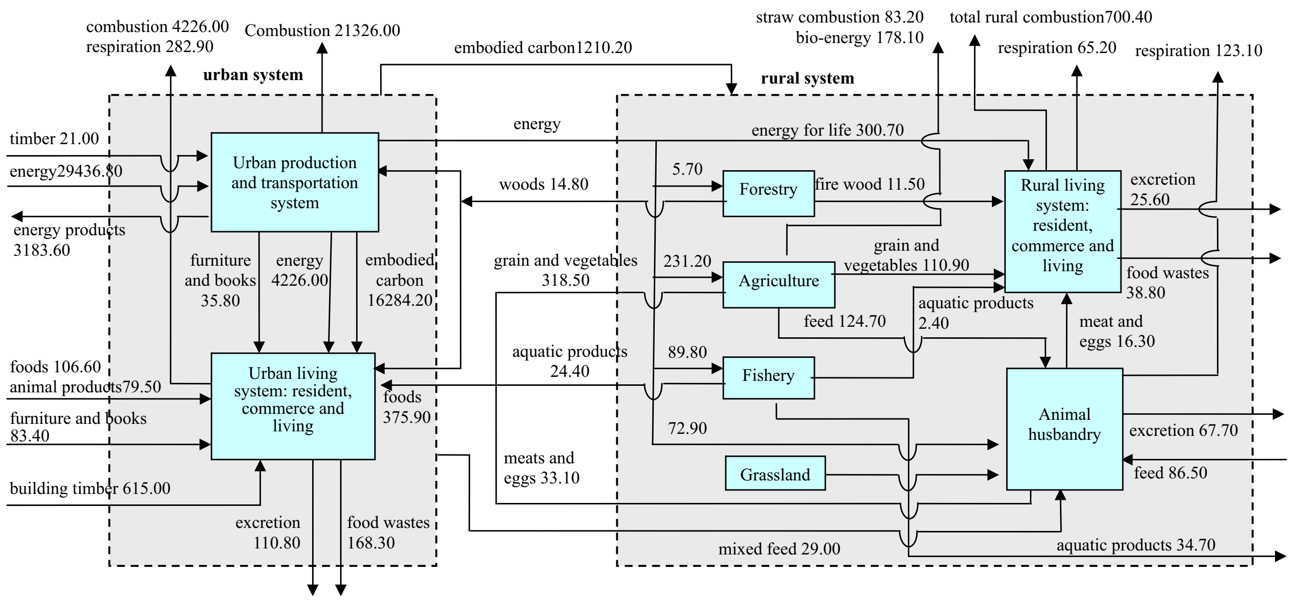


Fig. 2. Carbon flow map of Nanjing urban system in 2009 (unit: ktC/a).

Table 2
Carbon flow transition matrix of Nanjing urban system in 2009 (unit: ktC).

Sub-systems/items	Urban production and transportation system	Urban living system	Forestry	Agriculture	Fishery	Animal husbandry	Rural living system	Inner carbon flow (−)	Trade carbon flows (out)	Emission flows
Urban production and transportation system		4261.80	5.70	231.20	89.80	101.90	300.70	4991.10	3183.60	21326.00
Urban living system									279.20	4508.90
Forestry	14.80						11.50	26.30	0.00	17.20
Agriculture		318.50				124.70	110.90	554.10	0.00	314.40
Fishery		24.40					2.40	26.80	34.70	89.80
Animal husbandry		33.10					16.30	49.40	67.70	196.00
Rural living system									64.40	544.10
Inner carbon flow (+)	14.80	4637.80	5.70	231.20	89.80	226.60	441.80			
Trade carbon flows (in)	29457.80	884.30				86.50				

Notes: (1) Inner carbon flow (+) and inner carbon flow (−) means carbon flows in and out from certain sub-systems, respectively. (2) Trade flows and emission flows means the carbon exchanging between sub-systems and the external system.

living systems, make up the rural system. Here, agriculture represents only farmland activities.

4.1. Carbon flows between urban and external system

To clearly display carbon flow among the sub-systems, a carbon flow transition matrix is shown in Table 2. It showed that carbon input external to the Nanjing urban system was mainly in the form of energy, wood and timber, books, furniture, foods and feed. External energy input was largest (29.44 MtC) in 2009, which was mainly input to urban production and the transportation system. The carbon input external to the urban living system was mainly in the form of building wood and timber, food, books and furniture. Total input carbon was 884.30 ktC, in which building wood and timber was the largest (615.00 ktC). There was external animal feed input to animal husbandry, at 86.50 ktC (Table 2).

Carbon output from the urban system can be divided into trade flows and emission flows. Trade flows from the Nanjing urban system was mainly in the form of energy products, aquatic products and waste. Trade carbon flows from the urban production

Table 3
Carbon flows between urban and rural systems in Nanjing (unit: ktC).

Year	Direct carbon from rural to urban system	Direct carbon from urban to rural system	Embodied carbon from urban to rural system	Embodied carbon caused by urban consumption	Total carbon from urban to rural system	Net carbon from urban to rural system
2000	82.56	623.41	1396.09	4997.22	2019.49	1936.94
2001	101.63	589.99	1266.72	5121.23	1856.71	1755.08
2002	60.12	630.78	1288.44	5482.13	1919.22	1859.10
2003	128.83	552.40	1337.08	6860.32	1889.48	1760.65
2004	220.98	545.55	1504.06	8667.59	2049.61	1828.63
2005	239.73	550.57	1727.08	11280.16	2277.65	2037.92
2006	263.27	570.40	1802.17	12276.39	2372.57	2109.31
2007	265.67	590.31	1837.41	13791.15	2427.72	2162.05
2008	357.16	614.57	1456.23	14466.37	2070.80	1713.65
2009	390.77	700.42	1210.22	16284.18	1910.64	1519.87

system in the form of energy products was the largest (3.18 MtC) in 2009. While trade carbon flows out of Nanjing urban system in the form of aquatic products and waste was relatively small. There was also food waste and excretion that flowing from urban and rural living systems. Emission flows mainly originated from fossil energy and bio-energy consumption, respiration and straw combustion, in which emissions from energy consumption by the urban production system was the largest (21.33 MtC).

4.2. Carbon flows among different sub-systems of Nanjing

Fig. 2 shows the whole carbon flows among different sub-systems in Nanjing. The main carbonic materials in circulation are energy, food, wood and timber, animal feed, and others. The type, amount, direction and scale of the carbon flow processes were determined by industrial characteristics and energy consumption of each sub-system.

Carbon from the urban production and transportation systems mainly flows into other parts of the urban system in the form of energy and products, in which the most carbon flows into the urban residential, commercial and living systems. Carbon flow into the rural living system was mainly in the form of energy and embodied carbon. Total carbon flow from urban production and the transportation system was 4991.10 ktC in 2009. The urban residential, commercial and living systems received the most inner carbon input (4.64 MtC), such as energy products, books and furniture that principally came from the urban production and transportation system (4.26 MtC), food products that came from the agriculture production system, and wood products that came from the external system.

If we just consider two sub-systems, urban and rural, we clearly see that direct carbon flow from rural to urban was primarily in the form of wood and food products (390.77 ktC). Direct carbon flow from urban to rural was mainly in the form of energy (700.42 ktC), and carbon transported by the latter process was clearly more than that by the former. As to annual trends, direct carbon flow from rural to urban increased drastically, from 82.56 ktC in 2000 to 390.77 ktC in 2009 (Table 3). This was brought on by rapidly increasing food consumption and population growth. Comparatively speaking, direct carbon flow from the urban to rural system had a slight increasing trend, with fluctuation. This indicates that annual rural energy consumption increased slightly. For rural energy consumption, except for increasing rural living energy consumption, energy consumed in agriculture, forestry, animal husbandry and fishery all decreased or was stable after 2000. Along with urbanization, urban population growth, and a decrease of rural population, direct carbon flow from the rural to urban system may exceed the reverse flow in the future. Continued concentration of carbon consumption of food and energy in the city is the future trend of urban carbon flows.

4.3. Embodied carbon flows between urban and rural systems

According to the calculation method of embodied carbon, carbon emitted by energy consumption in industrial production was decomposed into rural and urban embodied carbon, by consumption of industrial products in the rural and urban living systems. From the results, we see that embodied carbon caused by urban consumption was much greater than that caused by rural consumption; these were 16.28 MtC and 1.21 MtC, respectively.

From the composition of embodied carbon, carbon embodied in industrial products caused by fossil energy consumption was much greater than that caused by electricity consumption. For example, embodied carbon flowing to the rural system caused by fossil energy and electricity was 1.02 MtC and 190.59 ktC, respectively; corresponding flows to the urban living system were 14.31 MtC and 1.98 MtC. This indicates that fossil energy was the most important energy type in Nanjing industrial processes.

The increasing rate of embodied carbon caused by urban consumption was obviously higher than that caused by rural consumption. From 2000 to 2009, embodied carbon caused by urban consumption increased from 5.00 MtC to 16.28 MtC. That caused by rural consumption declined from 1.40 MtC to 1.21 MtC (Table 3), which was largely caused by a decrease in rural consumption with decreasing rural population. This also indicates that the main circulation path of embodied carbon in industrial products was flowing from the urban production system to the urban living system, and a secondary path was flowing to the rural living system.

Comparing direct and indirect (embodied) carbon flows of urban and rural systems, we see that carbon flow from the urban to rural system of Nanjing was substantially greater than carbon flow in the reverse. Considering embodied carbon, we found that total carbon flowing from the urban to rural system was 1.91 MtC in 2009, but the reverse flow was just 390.77 ktC, about five times less. Thus, net carbon flow from the urban to rural system was about 1.52 MtC in 2009 (Table 3). From the annual changes of net carbon flow from urban to rural systems, we found that it increased beginning in 2000, reaching a peak in 2007 (2.16 MtC). It then declined to 1.52 MtC in 2009, which was caused by the large consumption of industrial products and electricity in rural systems in 2007.

4.4. Carbon flow efficiency of the Nanjing urban system

According to trade carbon flows and emission flows, carbon flow efficiency of the Nanjing urban system was assessed. Indexes such as carbon input and output intensity per unit GDP, carbon emission intensity per unit GDP, and carbon productivity were used to analyse carbon flow efficiency of the Nanjing urban system.

Carbon input into urban system was calculated according to terminal consumption of that system. There may be some waste or

Table 4
Changes of carbon emission intensity and carbon productivity of Nanjing.

Year	Trade carbon flows (in) (MtC)	Emission flows (MtC)	Trade carbon flows (out) (MtC)	Carbon input intensity per unit GDP (t/10^3 Yuan)	Carbon output intensity per unit GDP (t/10^3 Yuan)	Carbon emission intensity per unit GDP (t/10^3 Yuan)	Carbon productivity (10^3 Yuan /tC)	Per capita carbon emission (t)
2000	16.11	12.29	6.07	0.15	0.17	0.12	8.70	2.26
2001	15.46	12.58	5.32	0.13	0.15	0.11	9.50	2.27
2002	18.07	13.91	7.20	0.13	0.16	0.10	9.70	2.47
2003	20.36	16.13	7.37	0.13	0.15	0.10	9.60	2.82
2004	22.68	19.12	7.08	0.13	0.14	0.11	9.50	3.28
2005	27.61	23.63	7.80	0.13	0.15	0.11	8.80	3.97
2006	28.82	25.33	7.62	0.12	0.14	0.11	9.50	4.17
2007	30.16	27.56	6.71	0.11	0.12	0.10	10.10	4.47
2008	28.51	27.97	4.38	0.09	0.10	0.09	11.20	4.48
2009	30.43	30.69	3.63	0.09	0.10	0.09	11.30	4.87

Table 5
Uncertainty analysis of carbon flows in Nanjing by Monte Carlo simulation.

Estimated items	Mean (ktC)	Median (ktC)	Minimum (ktC)	Maximum (ktC)	Standard deviation (ktC)	Coefficient of variation (%)	Mean std. error (ktC)
Imported embodied carbon	12,428.27	12,378.98	9,097.76	15,928.41	1,410.33	9.99	6.31
Exported embodied carbon	14,895.57	14,990.20	11,138.65	18,221.43	1,467.42	20.21	6.56
Furniture carbon input	83.50	83.51	5.62	152.52	16.84	10.00	0.08
Urban living bio-mass input	32.02	31.67	28.60	37.93	2.11	9.85	0.01
Food carbon input	106.66	106.66	73.38	141.35	8.19	7.68	0.04
Carbon output of food wastes	136.41	136.41	81.27	191.83	13.64	20.17	0.06
Carbon in inner furniture circulation	35.78	35.78	4.77	63.37	7.23	11.35	0.03
Carbon embodied in petrochemical products	111.51	111.51	68.40	159.30	11.14	9.99	0.05
Production waste and loss	1,283.44	1,283.46	710.65	1,786.29	128.21	3.29	0.57
Total trade carbon flow(in)	42,809.76	42,760.06	39,465.56	46,318.63	1,410.48	2.92	6.31
Total trade carbon flow(out) and emission flow	50,501.92	50,594.15	46,571.95	54,153.74	1,472.88	6.59	6.59

carbon loss during the production process. Thus, the calculation of carbon input was less than the carbon output in the urban system. In this context, carbon input intensity per unit GDP (0.09 t/10^3 Yuan) was less than carbon output intensity per unit GDP (0.10 t/10^3 Yuan) in 2009 (Table 4). In general, with the rapid economic development of Nanjing, the increasing GDP rate has greatly exceeded that of carbon input and output. In past years, industrial structure adjustment and energy conservation and emission reduction policy was executed by the Nanjing government. Tertiary industry developed rapidly and represented over half the total GDP in Nanjing in 2008 [39]. This meant that economic development in Nanjing depended increasingly on tertiary industries. Further, some small and outdated chemical enterprises, cement and power plants were closed. Industries with high energy consumption were rigidly controlled. Through these measures, the increase of energy consumption and carbon emissions was clearly less than that of economic development. These are the major reasons for the decline in carbon emission intensity in Nanjing. Therefore, the carbon productivity and carbon flow efficiency in Nanjing has improved significantly after 2000 (Table 4).

We also studied human carbon emission intensity and carbon productivity of Nanjing. Results show that carbon emission intensity per unit GDP decreased, but carbon productivity increased after 2000. This reveals that carbon flow efficiency increased, i.e., economic production created by unit carbon emission was promoted. This means that energy use efficiency improved with the implementation of energy-saving and emission-reduction policies by the Nanjing government. With the economic development and industrial upgrade, carbon flow efficiency will further increase.

Table 4 shows that per capita carbon emission increased rapidly, from 2.26 t in 2000 to 4.87 t in 2009. This indicates that with the rapid economic growth and continuous improvement of living conditions, per capita energy consumption was increasing, which produced more carbon contamination and greater environmental pressure. Individuals are the most important terminal of carbon flows. Therefore, low-carbon policies should also consider the individual's role in urban carbon emission reduction.

4.5. Uncertainty analysis

Through Monte Carlo simulation, the distribution of uncertain carbon flow items was obtained (Table 5 and Fig. 3). It showed that the major uncertainty comes from imported and exported embodied carbon flows. Their mean values in 2009 were 12.43 Mt and 14.90 Mt, respectively. With the 95% confidence level, the imported embodied carbon was 9.82–1.517 Mt, while the exported embodied carbon was 11.96–17.52 Mt. It is clear that the exported values were higher than the imported ones, which was caused by the trade surplus of Nanjing. For the ignored carbon flows, we estimated that the mean urban living bio-mass input and production waste and loss were 32.02 kt and 1.28 Mt, respectively. Their ranges are shown in Table 5. The uncertainty of food and furniture carbon flows was also analysed (Table 5).

By adding the estimated value of uncertain items to the certain trade carbon flows and emission flows of Nanjing, the total trade carbon flow was estimated through random sampling using Crystal Ball. This showed that the mean input trade carbon flows and output carbon flows (including emission flows) were 42.81 Mt and 50.50 Mt, respectively. At the 95% confidence level, their ranges were 40.20–45.55 Mt and 47.56–53.14 Mt, respectively. Mean values of the output carbon flows (including emission flows) were about 18% greater than the input carbon flows, which means that local production strongly influenced the external system by larger carbon output. Because there is little local fossil energy

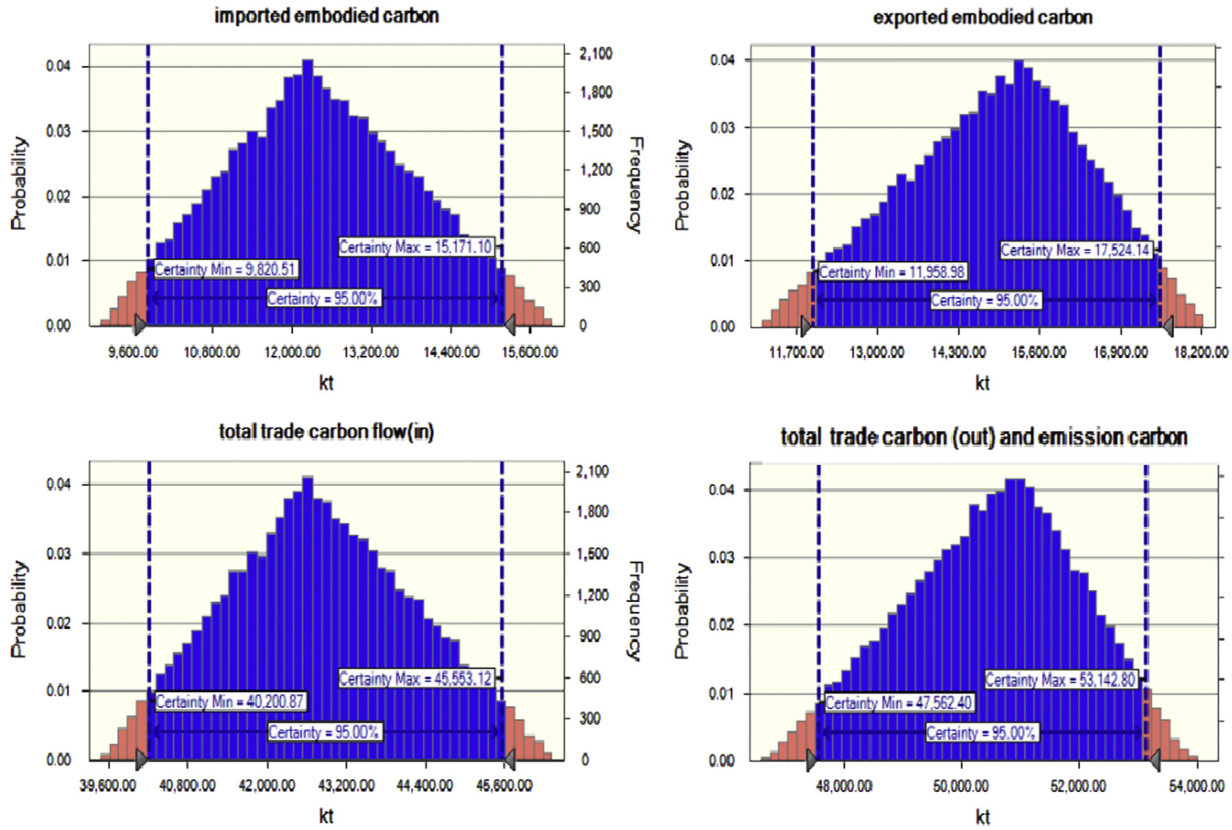


Fig. 3. The probability and frequency of uncertain carbon flows.

resource in Nanjing, the surplus carbon output most probably comes from rural production and agricultural carbonic materials. For the inner carbon flows, there is also uncertainty, such as carbon embodied in petrochemical products and inner furniture carbon flows. Their 2009 respective means were 111.51 kt and 35.78 kt (Table 5). Here, the petrochemical products include clothes, rubber and fibre, but do not include energy products. Generally, the uncertainties were largely from the imported and exported trade carbon flows, and the production waste and losses from the industrial production process.

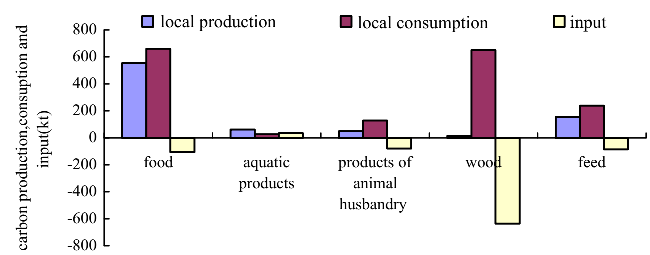


Fig. 4. Various carbon flow characteristics of several carbonic materials.

5. Discussion and policy implications

5.1. Discussion

5.1.1. Trade carbon flows

Flow paths of various carbonic materials (such as energy, food, wood or timber) were quite different from one another. Therefore, different carbon management strategies should be pursued according to these differences in trade carbon flows. Fossil energy is mostly imported from the external system to urban production and the transportation system, and in turn flows to other sub-systems of the urban system. The trade carbon flow characteristic of fossil energy in Nanjing city was similar with other cities [18,20,23,27]. However, the different regions have different flowing feature, for example, the proportion of imported fossil energy flows in Ensenada(Mexico) [18] and Siena (Italy) [20] was obviously lower than that in Nanjing city. This means that energy consumption in Nanjing city is the main driving force that brought the imported trade carbon flows, which is same as other Chinese cities: Shanghai [40], Tianjin [41], Beijing [42], Chongqing [43] and Xiamen [44]. This indicated that the energy consumption in industrial activities and transportation in Chinese cities highly contributes to the total carbon emission. It also suggests that urban industrial production and transportation system should be listed as the most important energy-saving sector, with the greatest carbon emission reduction potential in the future. Local production of several non-energy carbonic materials such as food, wood, feed and animal husbandry products were unable to meet the city's demand, requiring additional importation annually from the external system. In contrast, local aquatic products exceeded local consumption, so there were 34.70 kt aquatic products flowing to the external system in 2009 (Fig. 4). This means that improving local food and wood production by strengthening agriculture and forestry development is an important policy for balancing the urban carbon cycle. This will not only provide local carbonic materials for consumption, but also sequester carbon via photosynthesis.

In inner carbon flows, bio-mass energy is an important material flowing in the rural system. Firewood (about 11.50 ktC) from forestry toward the rural living system was mainly used for bio-energy, and straw (178.10 ktC) flowing from agriculture was used for combustion in that system. Bio-energy should be developed in the future to meet the increasing requirement for commercial energy in Nanjing, which will significantly decrease carbon emission by energy transportation and consumption.

5.1.2. *Embodied carbon flows*

Embodied carbon means carbon emissions from energy use during the production. It mainly includes the carbon embodied in industrial products and electricity. On county level, the trade goods are the main forms of embodied carbon [45–47]. On city level, we mainly consider the inner carbon flows embodied in goods and electricity between urban and rural systems. If the embodied carbon flows in Nanjing are taken into account, we see that carbon flow from urban to rural was much greater, and net carbon flowing from the urban to rural system was 1.52 MtC in 2009. Despite the fact that most food, wood and carbonic materials flow directly from rural to urban, there is much more carbon in the form of energy and embodied carbon (industrial products) flowing in the opposite direction. Overall, urban-to-rural carbon flow was clearly greater than the reverse. However, the result showed that net carbon flow from urban to rural systems declined from 1.94 MtC in 2000 to 1.52 MtC in 2009, together with a decrease in rural population and rapid growth of direct carbon flowing from rural to urban. With urbanization, rural population and consumption in Nanjing will decrease, which will in turn reduce net carbon flow from the urban to rural system. Meanwhile, total carbon embodied in industrial products and electricity will increase with urbanization and increase of production. So, the reduced net carbon flow from the urban to rural system will be substituted by growing consumption of the urban living system and increasing carbon flows from the urban to external system. This means that the carbon impact of the Nanjing urban system on external regions will be enhanced by increasing trade carbon flows out of the city. Generally speaking, the net carbon flows from the urban to rural system and trade flows to the external system were determined by the production of industrial products and electricity, as well as by the consumption scale of the urban and rural living systems. The embodied carbon represents emissions during industrial production caused by the demand of rural, urban or external consumption. Electricity transmission was also included in energy carbon flows. However, this transmission does not equal real carbon flow, but rather the indirect (embodied) carbon emission from electricity generation. Further, we see that the carbon flows embodied in fossil energy was much higher than in electricity, which is opposite to Macao [45]. This reflects not only the different products in trade flows in different regions, but also the different trading paths. For example, embodied carbon flows between urban and rural systems were considered in this paper, while the external trade flows was discussed in Macao studies [45].

5.1.3. *Emission flows*

We compared per capita carbon emissions in Nanjing and other Chinese or international cities. Here, carbon emission in Nanjing was converted to CO_2 by the coefficient of atomic weight (12/44). Fig. 5 shows that per capita carbon emission in Nanjing was 14.56 tCO_2/capita in 2005, lower than that of Lanzhou, Denver and Wuxi, but much higher than those of most Chinese or international cities [48–51], such as Beijing, Shanghai, New York and London (Fig. 5). Per capita carbon emission in Nanjing was also much greater than the global average (4.00 t per capita) and Chinese national average (3.65 t per capita) [40]. Nanjing has heavy chemical industries, with substantial energy consumption during the manufacturing processes, which emits more carbon. This means that the carbon cycle pressure in the city is much greater than most metropolitan cities in the world. With the economic development and rapid increase of total carbon emission, Nanjing will face strong pressure from carbon contamination, which will cause heavy burdens on urban energy security, environmental protection and carbon reduction.

As for the composition of carbon emissions in Nanjing, that emitted from fossil energy accounted for 82.0% in 2005 (Table 6). If considering carbon emission from wastes and industrial processes, industrial-related emissions constitute more than 96% of the total, much higher than that of other international cities. Emissions from industrial production mainly came from higher energy-consumption industries and certain special production processes (such as limestone, cement and glass). Research on carbon emission of some international cities [48–50] and Chinese cities [29,51] did not include emissions from bio-mass energy, methane emission and straw combustion. In contrast with other metropolitan areas, there is extensive cropland in Nanjing (37.0% of total land

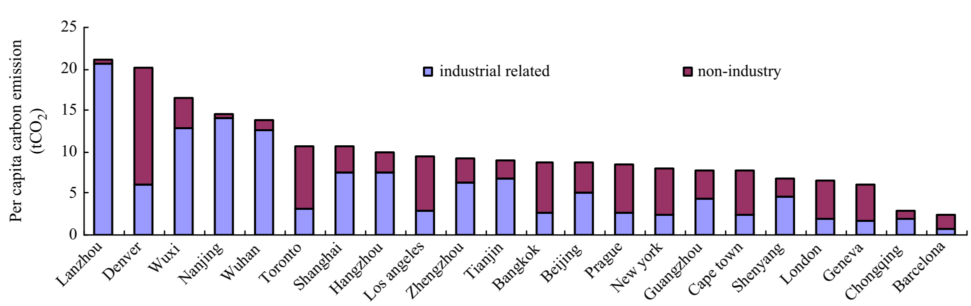


Fig. 5. Per capita carbon emissions in Nanjing and other cities in 2005. Note: Data of Chinese cities other than Nanjing is from Ref. [51], and those of international cities is from Ref. [48].

Table 6
Composition of carbon emissions of Nanjing (unit: ktC).

Year	Fossil energy	Biomass energy	Staw combustion	Industry	Methane emission	Animals	Human respiration	Solid waste	Waste water	Total
2000	9901.54	247.48	107.12	1235.31	55.42	224.97	449.43	43.31	28.25	12292.83
2001	9916.49	237.62	102.62	1524.38	48.53	252.56	421.84	46.83	28.19	12579.07
2002	10543.4	222.19	95.36	2219.63	42.89	259.73	450.8	48.55	28.02	13910.57
2003	12626.91	190.75	82.6	2441.74	37.37	266.93	402.91	55.69	28.41	16133.3
2004	15281.66	204.68	90.09	2768.64	43.7	256.39	381.69	62.83	28.54	19118.22
2005	19393.82	198.03	87.25	3194.53	45.22	245.62	366.17	70.39	29.17	23630.19
2006	20864.13	191.59	85.12	3492.66	41.6	176.2	373.45	72.73	29.26	25326.73
2007	23037.95	170.57	76.73	3633.85	38.62	130.61	365.12	74.72	29.37	27557.54
2008	23785.01	185.75	85.3	3269.57	42.75	134.94	355.54	77.1	29.42	27965.38
2009	26252.1	178.14	83.15	3553.75	41.03	129.14	348.08	79.48	29.04	30693.93

area in 2009). Therefore, carbon flows related to agricultural activities should also be emphasized. In Nanjing, total carbon emission from bio-mass energy, methane emission and straw combustion is about 300 ktC, which represents about 1% of the total. The straw utilization rate is very low, and large quantities are wasted by farmers. If this bio-energy could be fully used, substantial fossil energy would be saved.

Different country has different urban–rural division system. The trade carbon and emission flows were affected by the urban–rural spatial division [29,52]. Urban area is an administrative region in China. This generally includes several counties, in which agriculture production is dominant. The urban–rural division in the country strengthens the dependence of rural on city areas. This administrative system and urban–rural dual structure in China determined the carbon flow characteristics: (1) There are large bidirectional carbon flows between urban and rural systems, which include embodied carbon flows. (2) These large embodied carbon flows were mainly from rural consumption and ineffective transportation and agricultural activities. (3) In China, the administrative urban area is always larger than the actual urbanized area, which is opposite the case in most countries. Therefore, the result of carbon flow and carbon emissions here are slightly higher than other international cities.

Land use change, especially urban sprawl, inevitably modifies urban carbon flows and their efficiency. Per-unit area carbon emission and trade carbon flows in Nanjing during 2009 were 40.95 kt/km^2 and 48.87 kt/km^2, respectively. According to the current rate of increase of the built-up area, the emission flows and trade carbon flows will reach 66.59 Mt and 59.62 Mt in 2020, respectively. Corresponding per-unit area carbon emission and trade carbon flows will attain 65.44 kt/km^2 and 58.59 kt/km^2 in 2020. The urban expansion will not only occupy forest and cropland around the city, but also emit more carbon via road building, factory construction and energy consumption during land use activities. This indicates that urban expansion will drastically impact urban carbon flow efficiency in the future.

5.2. Policy implications

The results highlight several points that are important for policy-making in Nanjing, as follows.

The proportion of carbon emissions from energy use in Nanjing is much higher than other cities. Therefore, the energy structure should be adjusted, and clean energy (such as solar and bio-energy) should be developed. Nanjing is in the major grain-producing area of the Yangtze Plain. To fully exploit this advantage, bio-mass power generation should be strengthened through bio-mass utilization (wood, herbaceous and woody crops, manure and agro-industrial residues), which will not only effectively change the energy structure, but also reduce the smog and PM2.5 caused by the field straw combustion by farmers.

Heavy chemical industries in the city were the largest contributors to total carbon emission. Consequently, adjusting industrial structure, especially increasing the proportion of tertiary industries, should be included in economic development planning for the city. For example, industries with high energy consumption and carbon emission intensity, especially the cement and paper industry, should be gradually phased out, while the new energy industry, environmental protection and information industry should be encouraged in the future. The adjustment of industrial structure would decrease the carbon emission intensity, and basically lead the low-carbon transition of Nanjing in the long run.

Accumulating carbon flows (such as woods for construction and furniture) represents an important type of anthropogenic carbon sequestration. However, it only accounted for 2.4% of total trade carbon flows. Encouraging the use of accumulating carbon materials could not only replace traditional construction materials and reduce the energy use during the manufacturing of reinforced concrete, but also increase urban carbon storage for several decades. China is currently in the rapid urbanization process, the use of low-carbon construction materials will highly contribute to the sustainable urbanization mode. However, consuming carbon flows, such as foods and life energy, pertain to rigid types and should not be included as key targets for carbon emission reduction.

Carbon flow efficiency is determined by total carbon emissions, circulation period, and waste proportion of carbonic materials. To improve efficiency of carbon flows, the industrial chain should be extended and the circular economy should be promoted. For example, by resourceful utilization of municipal waste, we would not only reduce carbon emissions, but also save resources and create energy. Especially in petrochemical and wood processing industries, the saving and reuse of carbonic materials would significantly increase carbon flow efficiency.

Afforestation would compensate carbon emissions through carbon sequestration in natural processes. The strengthening of ecological management and environmental protection, and increase of urban green space and enhancement of carbon fixation efficiency of productive land, would not only create a green living environment, but also effectively reduce regional carbon emission and its intensity.

With rapid urbanization, per-unit area carbon emission will reach 65.44 kt/km^2 in 2020, which is 60% greater than that in 2009. Therefore, urban-scale and built-up areas should be restricted through scientific low-carbon urban planning, and repeated construction should be avoided. Further, the potential of constructive land should be tapped, and urban sprawl should be replaced by inner, intensive land use and urban renewal. The “compact city” pattern should be introduced in urban planning, which will not only avoid rapid urban expansion, but also reduce energy use through the shortening of distances between different urban functional districts.

In Nanjing, rural life and agricultural production require tremendous energy supply, which mostly comes from the city. Energy use in the rural system was not as convenient as in urban life, which increased the embodied carbon between the rural and urban system and reduced carbon flow efficiency. Therefore, the power condition for rural production and life should be improved. Renewable energy (such as biogas) should be developed to replace traditional fossil energy in the rural system, which will effectively decrease embodied carbon flows from the urban to rural system, and lead transformation of the rural energy consumption pattern.

In the energy flows from the urban to rural production systems, agricultural activities in cropland constitute 58%. In Nanjing, farming was also an ineffective activity, which consumed substantial direct energy and caused embodied carbon. Therefore, agricultural production conditions and practices should be innovated to adapt to mechanized agricultural production. This change will promote a change of rural lifestyle and radically improve agricultural efficiency. Furthermore, the dual urban–rural structure is a widespread problem in China. In the future, small rural towns should be developed, as should large cities. This will narrow the urban–rural gap, and increase energy efficiency through reducing large exchanges of products and energy between urban and rural areas. This strategy will influence the equilibrium between urban and rural territories in the long run.

Through the above policies, the efficiency of energy use will be increased through energy structure innovation and industrial structure adjustment, the carbon flow efficiency will be promoted through the development of circular economy, the carbon emissions will be compensated by afforestation and environmental protection, the carbon emission intensity will be decreased by the implement of “compact city” pattern and urban sprawl control, and the embodied carbon from urban to rural system will be reduced by the improvement of agricultural production conditions and the changing of dual urban-rural structure. All the above

strategies were expected to lead the wholly low-carbon transition of Nanjing city in the future.

6. Conclusions

Through establishment of a theoretical framework and calculation method, the carbon flows of the urban system and its efficiency in Nanjing was analysed. The main trade carbon flows and emission flows and their policy implications were discussed. We found that carbon flow of urban system is quite complex because it involves carbon flows in different levels and between different sectors. Carbon in the form of energy products is the main body of carbon flows between urban and external system, as well as between urban production system and urban living system. Among other different subsystems, food, wood and embodied carbon is the major part. If considering embodied carbon between the urban and rural system, carbon flow from urban to rural was substantially more than that from rural to urban. Therefore, renewable energy should be developed through bio-mass utilization to replace traditional fossil energy in the rural system, which will effectively decrease embodied carbon flows, and lead transformation of the rural energy consumption pattern. Results showed that traditional energy consumption, urbanization, agricultural activities, rural life demands and trade are key factors with major impact on urban carbon flow processes. Therefore, regulatory strategies to minimize carbon emissions and improve energy flow efficiency should be identified through the tracking of possible pathways that affect those carbon flows processes. In the future, adjusting energy and industry structure, developing renewable energy, intensive land use and urban expansion control, ecological management, and raising energy efficiency among different sub-systems should be adopted as the main approaches for Nanjing during the transition to a low-carbon economy.

The dual urban–rural structure is a widespread problem in China. In the future, small rural towns should be developed, as should large cities. This will narrow the urban–rural gap, and increase energy efficiency through reducing large exchanges of products and energy between urban and rural areas. This strategy will influence the carbon flows between urban and rural territories in the long run.

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Appendix A

See Tables A1–A4.

Table A1
Carbon content and carbon emission parameters of each energy type.

energy types	$H_{energy\text{-}i}$ kJ/kg (kJ/m^3)[a]	$C_{energy\text{-}i}$ (kgC/GJ)[b]	$M_{energy\text{-}i}$ (kgCH$_4$/TJ)[b]
Raw coal	20908.00	25.80	1.00
Cleaned coal	26344.00	26.21	1.00
Other washed coal	9408.50	26.95	1.00
Coal products	15909.80	26.60	1.00
Briquette coal	15909.80	26.60	1.00
Coal water slurry	9408.50	26.95	1.00
Pulverized coal	9408.50	26.95	1.00
Coke	28435.00	29.20	1.00
Other coke chemicals	34332.00	26.60	3.00
Coke oven gas	17353.50	12.10	1.00
Blast furnace gas	2985.19	70.80	1.00
Other coal gas	16970.33	60.20	1.00
Natural gas	38931.00	15.30	1.00
Crude oil	41816.00	20.00	3.00
Gasoline	43070.00	18.90	3.00
Kerosene	43070.00	19.60	3.00
Diesel	42652.00	20.20	3.00
Fuel oil	41816.00	21.10	3.00
Liquefied petroleum gas	50179.00	17.20	1.00
Refinery gas	46055.00	15.70	1.00
Coal tar	33453.00	20.00	3.00
Other oil products	37681.20	20.00	3.00
Heating power	1(kJ/kJ)	26.95	1.00
Electricity	3596(kJ/kWh)	26.95	1.00

[a] Ref. [30].
[b] Ref. [31].

Table A2
Economic coefficient, moisture content and carbon absorption rate of each crop type.

Crop types	$H_{crop\text{-}i}$ [a]	$P_{water\text{-}i}$ [b]	$C_{crop\text{-}i}$ (kgC/kg)[a]
Rice	0.45	0.14	0.41
Wheat	0.40	0.13	0.49
Corn	0.40	0.14	0.47
Sorghum	0.35	0.15	0.45
Millet	0.40	0.14	0.45
Potato	0.70	0.13	0.42
Soybean	0.35	0.13	0.45
Other crops	0.40	0.13	0.45
Cotton	0.10	0.08	0.45
Rape	0.25	0.09	0.45
Sunflower	0.30	0.09	0.45
Peanut	0.43	0.09	0.45
Sugarcane	0.50	0.13	0.45
Hemp	0.39	0.13	0.45
Beet	0.70	0.13	0.41
Tobacco	0.55	0.08	0.45

[a] Ref. [32].
[b] Ref. [33].

Table A3
Carbon content of each food type (Source: Luo et al., [25]).

Food types	Carbon content (kgC/kg)	Food types	Carbon content (kgC/kg)
Grain	0.33	Meat	0.25
Vegetables	0.03	Aquatic Product	0.14
Fruits	0.05	Egg	0.15
Vegetable Oil	0.77	Candy	0.34
Wine	0.04	Sugar	0.40
Milk	0.06	Tea	0.34

Table A4
The details of data sources.

Data inventory	Sources
Annual population, GDP, crop yield (crop types were shown in Table A2), industrial output	Nanjing Statistical Bureau, 2010a [a]
Food consumption (food types were shown in Table A3)	Statistical Bureau of Jiangsu Province, 2010 [b]
Industrial energy consumption (energy types were shown in Table A1)	Environmental Report of Jiangsu Province [e] Nanjing Statistical Bureau, 2010b [c]
Living energy consumption (electricity and Natural Gas)	Ministry of Housing and Urban–rural Development of China, 2010 [d] Urban Construction Statistical Report of Jiangsu Province [f]
Annual floor area and per capita floor area of each building type	Annual Report on Urban Construction Development of Nanjing [g]
Output and circulation data of wood and wood products(such as books and furniture)	provided by Nanjing Statistical Bureau

[a] Ref. [53].
[b] Ref. [54].
[c] Ref. [55].
[d] Ref. [56].
[e] Environmental Protection Department of Jiangsu Province. Environmental Report of Jiangsu Province; 2010.
[f] Construction Department of Jiangsu Province. Urban Construction Statistical Report of Jiangsu Province;2010.
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